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The Blazhko Project: Joint Efforts in Solving a Century-old Problem

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Abstract. Almost a century after its discovery, the phenomenon of amplitude and/or phase modulation, observed in a large percentage of the RR Lyrae stars, still lacks widely acceptable theoretical understanding. Recent attempts to theoretically explain the effect focus on two alternatives: the magnetic models and the resonances models, both involving the presence of nonradial pulsation components.

In this paper the *Blazhko Project* is presented, a larger international collaboration focused on understanding the Blazhko effect. The aim of the project is to combine spectroscopic and photometric data from a sample of well-selected Blazhko and non-Blazhko stars, in order to reveal crucial information on the physical mechanism responsible for the modulation.

The possible key to the century-old Blazhko puzzle lies in the detailed study of the line profile variations (LPV) over the pulsation and Blazhko cycle. We briefly discuss the methodology of the project.

1. RR Lyrae Stars and the Blazhko Effect

RR Lyrae stars have been studied for over a century now, and play an important role in astrophysics. These pulsating variables have periods of 0.2–1.1 day, and show brightness variations of the order of a magnitude. Until not so long ago, they were considered to be prototypes of radially pulsating stars.

The most intriguing subclass of RR Lyrae stars consists of stars showing the Blazhko effect, the phenomenon of amplitude or phase modulation. These stars have light curves that are modulated on time scales of typically tens to hundreds of days (Fig. 1). Blazhko (1907) was the first to report this phenomenon in RW Dra. The estimated incidence rate of Blazhko variables among the galactic RRab stars (fundamental mode pulsators) is about 20–30% (Szeidl 1988; Moskalik & Poretti 2002). For the RRc Blazhko stars (first overtone pulsators) this rate is less than 5%. In the LMC the incidence rate for RRab stars is only half as large, which is probably a metallicity effect.

2. Past and Present Studies of the Blazhko Effect

The Blazhko effect has been the frequent subject of photographic and photometric studies (e.g., Szeidl & Kollath 2000). Traditionally, the phenomenon was studied by means of $O - C$ analysis. Therefore, the observations were in general strongly biased towards the ascending branch and maximum phase of the primary light curve, a sampling pernicious for the Fourier analysis recently used

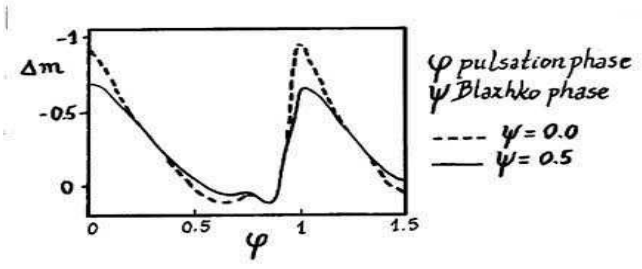

Figure 1. Illustration of the light curve changes of a Blazhko star.

to describe the changes in the light curve throughout the Blazhko cycle. Rigorous frequency analyses of photometric data covering complete light curves were carried out for northern field Blazhko stars by e.g., Borkowski (1980), Kovacs (1995), Smith et al. (2003), just to mention a few. For RR Lyr, the brightest Blazhko star, important spectroscopic studies were performed by Struve & Blaauw (1948) and Preston et al. (1965).

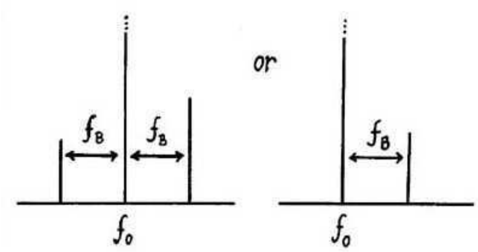

Figure 2. Triplet or doublet in the frequency spectrum of a Blazhko star.

For a long time the presence of the Blazhko effect in RRc stars was an open question: because of the small changes in the height of maximum of their light curves it was more difficult to detect. The controversy was resolved by the systematic studies of accurate CCD data of globular clusters and the large variable-star data bases resulting from microlensing surveys (e.g., MACHO, OGLE). These studies have cast a new light upon the study of RR Lyrae variability (Moskalik & Poretti 2003; Alcock et al. 2000, 2003), and have yielded important statistics on the phenomenology of the Blazhko effect.

The frequency spectra of light and radial-velocity curves of RR Lyrae Blazhko stars exhibit either a doublet structure or an equally-spaced triplet structure around the main pulsation frequency and its harmonics, with a small frequency separation corresponding to the Blazhko frequency (Fig. 2). The observed period ratios are 0.95–1.05, which excludes the possibility of another radial mode being excited. The present data sample indicates that there could be a continuous transition between the variables showing an equidistant triplet and those displaying only a close doublet, suggesting that both features are the result of the same phenomenon. A large majority of the Blazhko stars have a larger modulation peak at the higher (rather than the lower) frequency side of the main pulsation component.

Another interesting fact is the absence of the Blazhko effect among the long period RRab stars (Smith 1981). Blazhko stars at their greatest light amplitude fall approximately on the curve of amplitude versus period as defined by stars with regular light curves. This indicates that the Blazhko effect tends to reduce the maximum light level.

Period changes are a common feature in RR Lyrae stars, and also occur in Blazhko stars (Smith 1995; Szeidl & Kollath 2000; LaCluyzé et al. 2002). The observed period variability is too fast to be of evolutionary nature. In some stars the Blazhko effect ceased. Some well-studied field Blazhko stars are reported to display, besides their Blazhko cycles, also very long periods of the order of years. RR Lyrae, for example, shows a cycle of about 4 years, at the end of which the strength of the modulation suddenly decreases, and a phase shift of about 10 days occurs in the Blazhko cycle. This phenomenon is still unexplained, though it has been used as an argument for the magnetic models.

3. Explanations for the Blazhko Effect in RR Lyrae Stars

The most plausible hypotheses to explain the phenomenon focus on two types of models, both involving nonradial pulsation components (Kovacs 2002), as displayed in Fig. 3.

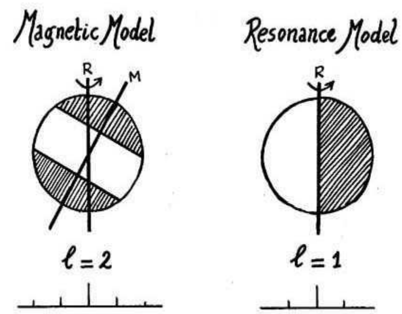

Figure 3. The two prevailing models for the Blazhko effect.

The Resonance Models

The resonance models are based on a (nonlinear) resonance between the radial fundamental mode and a nonradial mode. In these models the dipole ($\ell = 1$) modes have the highest probability to be nonlinearly excited (Cox 1993; Van Hoolst et al. 1998). Nowakowski & Dziembowski (2001) predict significant amplitude and phase modulation in the case of excitation of a rotationally split $m = \pm 1$ pair. The modulation period is determined by the rotation rate (currently unknown) and the Brunt-Väisälä frequency in the deepest part of the radiative interior. Peterson (1996) measured the line-widths via cross-correlation for 27 RR Lyrae stars and obtained an upper limit for $v \sin i$ of 10 km s^{-1}.

The Magnetic Models

The magnetic models, like the simple oblique pulsator model for roAp stars (Kurtz 1982), suppose that Blazhko stars have a magnetic field inclined to the stellar rotation axis (Cousens 1983; Shibahashi & Takata 1995). The main radial mode is deformed by the magnetic field to have an additional quadrupole component ($\ell = 2$), for which the symmetry axis coincides with the magnetic axis. Due to the star's rotation our view of the pulsation components changes, causing the observed amplitude modulation. Shibahashi & Takata (1995) predict a quintuplet structure in the frequency spectrum, but also show that the quintuplet looks almost like a triplet for certain geometrical configurations. Depending on which of the side components we then observe, the Blazhko period is supposed to be equal to the rotation period or half of the rotation period. According to the latest model, a magnetic field of about 1 kG is needed in this model for the amplitude modulation to be observable. Whereas Babcock (1958) and Romanov et al. (1994) reported a variable magnetic field in RR Lyr with a strength up to 1.5 kG, Preston (1967) and Chadid et al. (2001, 2004) contradict these measurements.

Remaining Questions

In both the magnetic (Shibahashi 2000) and the resonance models (Nowakowski & Dziembowski 2001) the pulsation amplitudes are considered to be constant. The observed modulation of the light curve is a consequence of rotation. The degree of modulation is aspect-dependent in both models. Each of the models predicts modulation components of equal amplitudes, in sharp contrast to the large majority of the frequency patterns observed. The question of why RRc Blazhko stars have significantly lower incidence rates has not yet been addressed in the magnetic model. The resonance model does predict a lower probability for first overtone pulsators to show amplitude modulation, although still not in the degree observed. Deviations from strict amplitude/phase modulations (see e.g., Szeidl 1988; Smith et al. 2002) need to be explained by future modelling. The different incidence rates in different populations (LMC and Galactic Bulge), probably related to metallicity (Moskalik & Poretti 2002; Alcock et al. 2003), have yet to be taken into account. Finally, convective turbulence may play a role in driving/quenching the Blazhko effect.

We can conclude that *the basic physical understanding of the Blazhko phenomenon is still missing*, and the viable models need fine-tuning. As both models for explaining the Blazhko effect are based on the presence of nonradial components, their detection and identification is of utmost importance for understanding the mechanism behind the amplitude modulation.

4. New Developments in Line-profile Analysis

Up to now most observational studies of Blazhko stars were based on photometric data. High-resolution line profiles offer much better diagnostics to find and identify nonradial oscillation components in pulsating stars. A few years ago the first line profile study aiming at an identification of the nonradial mode(s) was carried out by Kolenberg et al. (2003). It was based on a set of 669 high-resolution

($R = 40000$) spectra of RR Lyr, obtained with the spectrograph ELODIE attached to the 1.93-m telescope at the Observatoire de Haute-Provence in France (Chadid et al. 1999). A detailed study of the variations of the FeII line profile at 4923.921 Å led to a clear detection of nonradial pulsation components in the star. By means of an adapted version of the moment method (Balona 1986; Aerts 1996; Kolenberg 2002), the detected nonradial modes were identified as nonaxisymmetric (with respect to the rotation axis) modes of degree $\ell \leq 3$ (see below). The incomplete coverage of the data over the Blazhko cycle hampered a more precise identification. As this kind of analysis is a first essential step towards a decisive confrontation between the theoretical models and the observations, more spectroscopic data, additional data, better spread over the Blazhko cycle, and similar data sets of additional (Blazhko) RR Lyrae stars are highly desired.

5. The Blazhko Project

The Blazhko Project is a large international collaboration, set up to join efforts in obtaining a better understanding of the Blazhko phenomenon in RR Lyrae stars. The project was founded in Vienna and started its activities in the autumn of 2003.

Methodology

The starting point for improving the modelling is an extensive data of a *limited sample* of field RR Lyr Blazhko and non-Blazhko stars: a few RRab Blazhko stars, carefully selected in hemispheres, and also one RRc Blazhko target. Important is the inclusion of a few well-selected non-modulated RR Lyrae stars in the target list, of which similar data are being gained, to be compared with the Blazhko stars.

The required data set consists of high-resolution ($R \geq 40000$), high-S/N ($\geq$ 100) spectroscopic data evenly spread over the Blazhko cycle for the target stars. A few very detailed snapshots ($S/N \geq 200$) are being (and will be) obtained with telescopes of the 8-m class, and will help to distinguish between different nonradial modes (see below). Simulation studies reveal how many high-resolution data are minimally needed to be able to disentangle the modes, and what would be their optimal time spread. Additional radial velocities over a longer time base can be obtained with smaller telescopes, and provide essential information to interpret the line profile variations. Finally, photometric data gathered over a time base of at least a year are needed to ensure the required frequency resolution. For the interpretation of the data we will use the available spectroscopic identification methods (described below), as well as combined techniques presently being developed (see Zima et al. 2004).

Line Profile Analysis The crucial question to be solved by the line profile modelling is whether the modulation can be represented by a low-order nonradial surface velocity structure. In our line profile modelling we follow the formalism described by Aerts & Eyer (2000). The subtle changes in the line profile variations caused by different pulsation parameters can be tested by our simulations, as illustrated in Fig. 4. The confrontation of our simulations with the already existing observations of RR Lyrae confirmed that modes of $\ell > 3$ may be eliminated on the ground that their intrinsic amplitude would have to be larger than the already large amplitude of the radial mode.

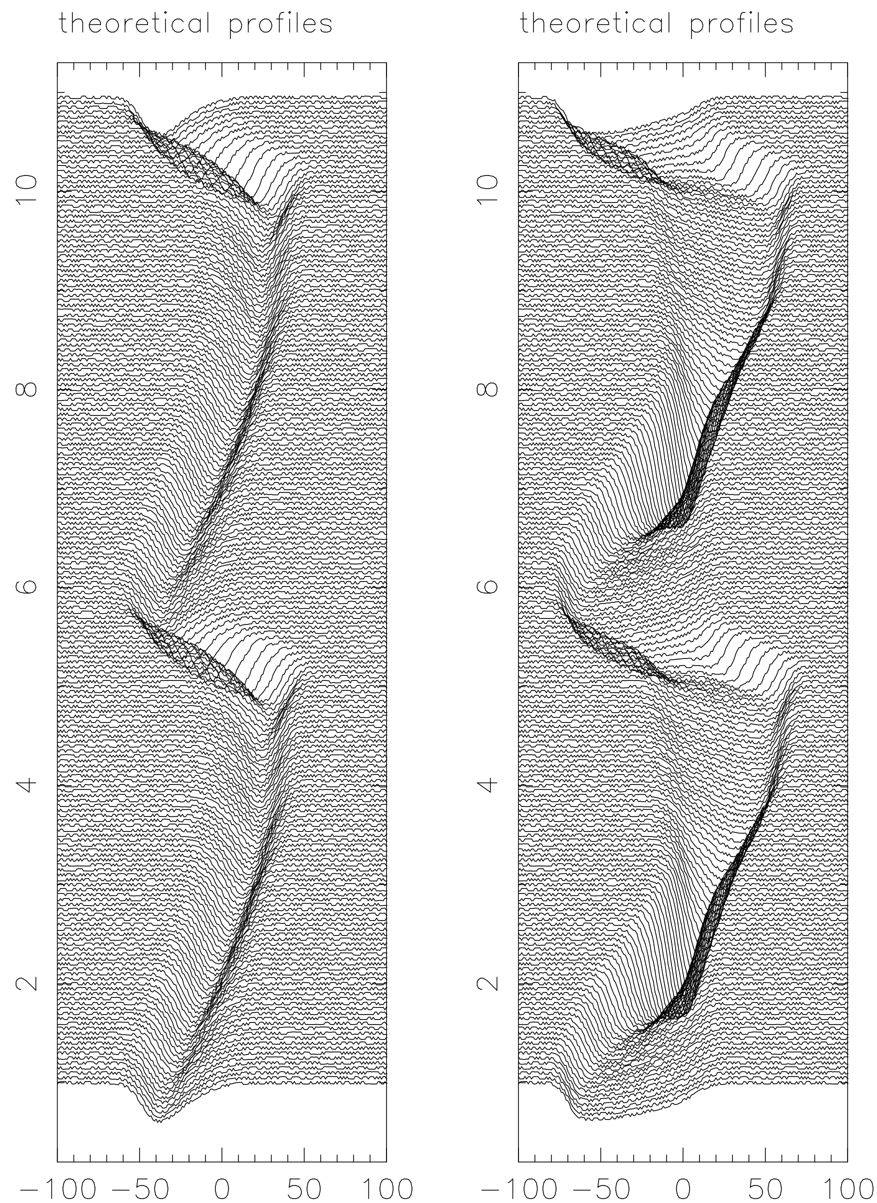

Figure 4. Illustration of the influence of a nonradial mode upon the line profile variations. The x-axis gives the velocity expressed in $\mathrm{km\,s^{-1}}$ and the y-axis is the normalized flux. The profiles for increasing phase are shifted in flux for visual inspection. Theoretical line profiles resulting from a nonlinear radial mode (left panel) and the interactions of the same radial mode with a nonradial mode (2,-1) (right panel). In this example the nonradial mode has a pulsation amplitude six times smaller than the radial mode.

A possible key to the century-old Blazhko puzzle is in the very detailed study of the line profile variations over the pulsation cycle at different phases in the Blazhko cycle. The two competing models, the resonance model and the oblique pulsator model, produce subtly different line profile variations requiring spectra with the highest possible resolution and S/N.

By studying the pixel-to-pixel intensity variations of a line profile, amplitude and phase diagrams can be calculated for each detected frequency. For stars rotating fast enough these diagrams can serve as a diagnostic for mode identification, as put forward by Telting & Schrijvers (1997). For stars in which the pulsation frequency is certainly much higher than the rotation frequency, like RR Lyrae stars, the technique cannot be used for mode identification, but the diagrams are informative about the amplitude and phase behavior of the separate modes acting in the star.

Moment Method

The moment method was the first quantitative spectroscopic identification method. It was introduced by Balona (1986) as an alternative to the line-profile fitting technique. Aerts et al. (1992) extended the method and applied it for the first time to the line-profile variations of a real star. The normalized moments are one-dimensional quantities obtained by taking integrals of the line profiles. Aerts et al. (1992) showed that the first three moments contain enough information to give a good description of the spectral line considered. The idea behind the method is to compare the observed time variations of the moments to theoretically calculated moments, and to select for which pulsation mode (ℓ, m) the agreement is best. The reduction of the number of free parameters compared to the identification by line profile modelling results in a considerable gain of computation time while scanning all candidate modes. The method was developed in a linear pulsation framework and proved to be very successful in identifying nonradial pulsations in main sequence stars.

The method of Aerts (1996) was adapted to be applicable to a star with a nonlinear radial mode such as RR Lyrae (Kolenberg 2002). For the frequencies related to both side peaks in the triplet structure around the main frequency, three possible $(\ell, |m|)$ combinations were selected as best solutions: the non-axisymmetric $\ell = 1$ and $\ell = 2$ modes. A subsequent line profile fitting on the observed profiles confirmed these results (see also Kolenberg et al. 2003). However, they need to be checked on other data. The new spectroscopic data will allow for a precise identification of the modes responsible for the observed modulation.

Present Status

At the time of writing the project has more than 30 collaborators – observational and theoretical – in both hemispheres.

In 2004, an extensive spectroscopic and photometric campaign was dedicated to RR Lyrae, gathering data from 10 different locations/observatories. On the southern hemisphere, a sample of relatively unstudied Blazhko stars is being sampled photometrically, with the aim of fixing Blazhko periods and select the best targets for a spectroscopic study.

From the theoretical side, line profile variations are being studied for stars pulsating in a radial mode, modulated by nonradial components with close frequencies. These experiments also serve to determine the optimal time spread for the observations, in order to make efficient use of telescope time. Theoretical studies may also reveal how light curves are influenced at maximum/minimum light by the interaction of different modes. Finally, spectroscopic mode identification methods and their applicability are being tested in a Vienna-Leuven collaboration (Zima et al. 2004)

The status of the Blazhko Project can be checked on a new website dedicated to the collaboration: `http://www.astro.univie.ac.at/ blazhko/`.

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References

Aerts, C. 1996, A&A, 314, 115
Alcock, C., Allsman, R., Alves, et al. 2000, ApJ, 542, 257
Alcock, C., Alves, D. R., Becker, A., et al. 2003, ApJ598, 597
Babcock, H. W. 1958, ApJS, 3,141
Balona, L. A. 1986, MNRAS, 219, 111
Blazhko, H. W. 1907, Astron. Nachr., 175, 325
Borkowski, K. J. 1980, Acta Astron., 30, 393
Chadid, M., Kolenberg, K., Aerts, C., & Gillet, D. 1999, A&A352, 201
Chadid, M., Wade, G. A., Shorlin, S. L. S., & Landstreet, J. D. 1999, A&A, 413, 1087
Cousens, A. 1983, MNRAS, 203, 1171
Cox, A. N. 1993, Proc. IAU Coll., 139, 409
Kolenberg, K. 2002, PhD Thesis, http://www.ster.kuleuven.ac.be/pub/ kolenberg_phd/
Kolenberg, K., Aerts, C., Fokin, et al. 2003, ASP Conf. Ser., 259, 396
Kovacs, G. 1995, A&A, 295, 693
Kovacs, G. 2002, ASP Conf. Ser., 259, 396
Kurtz, D. W. 1982, MNRAS, 200, 807
LaCluyzé, A., Smith. H. A., Gil, E.-M., et al., ASP Conf. Ser., 259, 416
Moskalik, P., & Poretti, E. 2003, A&A, 398, 213
Nowakowski, R. M., & Dziembowski, W. A. 2001, Acta Astron., 51, 5
Peterson, R. C., Carney, B. W., & Latham, D. W. 1996, ApJ, 465, 47
Preston, G. W., Smak, J., & Paczyński, B. 1965, ApJS, 12, 99
Preston, G. W., 1967, in The Magnetic and Related Stars, 26
Shibahashi, H., & Takata, M. 1995, ASP Conf. Ser., 83, 42
Smith, H. A. 1981, PASP, 93, 721
Smith, H. A. 1995, RR Lyrae stars, Cambridge University Press
Smith, H. A., Church, J. A., et al. 1981, PASP, 115, 43
Struve, O., & Blaauw, A. 1948, ApJ, 93, 721
Szeidl, B., & Kollath, Z. 2000, ASP Conf. Ser. 203, 281
Van Hoolst, T., Dziembowski, W. D., & Kawaler, S. D. 1998, MNRAS, 297, 536
Zima, W., Kolenberg, K., Briquet, M., & Breger, M. 2004, CoAst, 144, 5